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Acoustical and perceptual assessment of water sounds and their use over road traffic noise[a)]

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This paper examines physical and perceptual properties of water sounds generated by small to medium sized water features that have applications for road traffic noise masking. A large variety of water sounds were produced in the laboratory by varying design parameters. Analysis showed that estimations can be made on how these parameters affect sound pressure levels, frequency content, and psychoacoustic properties. Comparisons with road traffic noise showed that there is a mismatch between the frequency responses of traffic noise and water sounds, with the exception of waterfalls with high flow rates, which can generate large low frequency levels comparable to traffic noise. Perceptual assessments were carried out in the context of peacefulness and relaxation, where both water sounds and noise from dense road traffic were audible. Results showed that water sounds should be similar or not less than 3 dB below the road traffic noise level (confirming previous research), and that stream sounds tend to be preferred to fountain sounds, which are in turn preferred to waterfall sounds. Analysis made on groups of sounds also indicated that low sharpness and large temporal variations were preferred on average, although no acoustical or psychoacoustical parameter correlated well with the individual sound preferences.
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I. INTRODUCTION

In view of improving quality of life and comfort, the acoustic use of water features is increasingly being considered in the built environment due to the inherent positive qualities of water sounds[1] and their ability to mask noise.[2–5] Most of the acoustic research looking at water features has been made in the context of the soundscape,[6] which relies on both physical characteristics and mental perception of the aural environment. Soundscape studies are often influenced by multiple sources and factors, which make it difficult to analyze and understand water sounds in isolation, but recent studies have used methods in which the water sounds could be controlled and examined accurately.[2–5,7] These studies focused on the use of water sounds over road traffic noise and are reviewed in the following in some detail, due to their relevance to the research presented.

Watts *et al*.[2] carried out laboratory measurements to capture water generated sounds under controlled conditions, and used auditory tests to assess the tranquility of the sounds. The results showed that the water stream and cavities used could not produce sound pressure levels at low frequencies that are high enough to mask traffic noise. However, auditory tests indicated that improvements in tranquility could be obtained even for low levels of masking, which might have been due to the distracting effect of natural sounds. The study also found that increases in sharpness (i.e., high frequency content) were closely associated with improvements in tranquility.

Jeon *et al*.[4] carried out qualitative perceptual assessment of urban soundscapes using auditory tests, and found that water sounds were the best sounds to use for enhancing the urban soundscape, compared to sounds generated by birds, wind, and the bell of a church. Furthermore, the study found that the water sounds should be similar or not less than 3 dB below the urban noise level.

More recently, Jeon *et al*.[5] also studied water sounds of large features using aural and visual tests that were analyzed in terms of psychoacoustical metrics and acoustical measures. Results indicated that preference scores were affected by the acoustical characteristics of water sounds and visual images of water features, and that sharpness was a dominant factor of soundscape perception. Furthermore, it was found that the preference of the urban soundscape can be described by adjectives such as freshness (high sharpness) and calmness (low sharpness).

Nilsson *et al*.[3] found that the sound of a fountain can reduce the loudness of road traffic noise, and De Coensel *et al*.[7] showed that this occurs only if road traffic noise has low temporal variability, whilst adding bird sound can significantly enhance soundscape pleasantness and eventfulness even for road traffic noise with high temporal variability. The latter suggests that temporal variability, meaning of the sound and informational masking effects such as target-masker,[8] can affect the perception of water sounds against road traffic noise.

In addition to these findings, an understanding of the mechanisms affecting water sound generation is essential for

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the analysis of results given in Sec. III. In the case of water falling over water, a low level impact sound originates from shock waves occurring at the contact region, followed by the formation of vibrating bubbles in the water.[9] The latter sound tends to be dominant and exhibits tonal properties that are a function of the size of the bubble, as the resonance frequency of the bubble is inversely proportional to its diameter.[10] Although these fundamental mechanisms are well known, water sounds are complex and difficult to predict, a reason why experimental research can help in understanding the interaction between design factors and acoustic properties of water features.

The above-discussed experimental studies[2–5,7] have contributed to the understanding of water generated sounds and their perception. The present study extends the range of water features and streams of small to medium size previously examined by analyzing waterfalls, fountains, cascades, and jets, which can typically be found in gardens and parks. The aim of the study is to investigate how the design of these water features can affect their acoustical and perceptual properties when used over road traffic noise to promote peacefulness and relaxation. This is achieved by examining the impact of design factors (flow rate, height of falling water, waterfall's edge design, and impact materials) on acoustical and psychoacoustical parameters, and by identifying preferences (sound pressure level and water sounds), and how these correlate with the physical properties of water features. Ultimately, the findings obtained will indicate which water sounds and designs are more suitable for improving peacefulness and relaxation within gardens and parks where road traffic noise is audible.

II. TEST STRUCTURE AND PROCEDURES

A. Test structure

A variety of waterfalls, fountains, cascades, and jets were tested in the laboratory under controlled conditions. The structure built (Fig. 1) consisted of a sump tank encased in the floor and into which water falls (2.0 m long × 1.2 m wide × 1.2 m high), and a tank fixed at a higher level for waterfalls' testing (1.5 m long × 0.5 m wide × 0.5 m high). Two submersible pumps of low noise level (i.e., not affecting measurements) were placed in the sump tank and used to circulate water to the upper tank or to fountains' attachments with a variable flow rate of up to 150 l/min; the upper tank was fixed to a frame and could be moved to reach a maximum height of 2.5 m above the floor level. Absorption panels were also installed around the structure to minimize sound reflections from adjacent surfaces. All the data presented in this paper were obtained from the laboratory, with the exception of one field test made on a shallow stream that was used for the auditory tests.

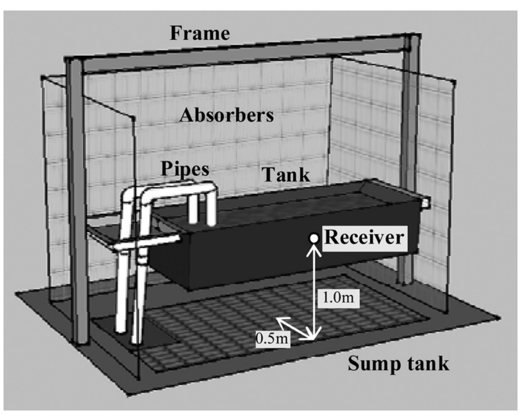

FIG. 1. Three dimensional sketch of laboratory structure used for testing water sounds (drawing not to scale).

B. Measurement procedures

Laboratory measurements were carried out at a distance of 0.5 m from the center section of the sump tank (impact area of falling water) and 1 m above floor level (Fig. 1). This receiver position was chosen for being representative of a person seated in the vicinity of a water feature, whilst still being largely dominated by the direct field (i.e., negligible influence from the reverberant field of the large laboratory). For the single field test used, measurements were undertaken at the edge of the stream, 1 m above the ground.

Different waterfalls, fountain designs, cascades, as well as combinations of upward jets were tested, and some examples are given in Fig. 2. Waterfalls were tested with different widths, heights of falling water, flow rates, and impact materials (concrete, metal, stones, boulders, and gravel). Furthermore, different waterfall edges were used, including a plain edge, a sawtooth shaped edge, and an edge made of small holes (2 mm diameter), as these were found to be representative of a variety of edge conditions. A plain edge results in a uniform "curtain" of water falling over the impact material, whilst a sawtooth edge design creates several streams of water and is effectively equivalent to an edge comprising large holes, but has the advantage of not being limited in terms of diameter's size. The edge made of small holes was also useful for representing a "rain" type of water distribution.

Measured data included physical parameters (spectrum and sound pressure levels) as well as psychoacoustical parameters (loudness, sharpness, roughness, and pitch strength). Acoustic parameters were measured using an integrating-averaging sound level meter Brüel & Kjaer Type 2250 (Naerum, Denmark), with a data averaging period of 20 s. In the following sections, frequency responses are presented in octave bands for the 63 Hz–16 kHz range; lower frequencies are not included, because of the low frequency background noise from building services which was often present in the laboratory. Audio recordings were also carried out with a digital sound recorder Zoom H4n connected to Brüel & Kjaer Type 4190 1/2 in. microphones, which were in turn attached outside the ears of a lightweight dummy head Sennheiser MKE 2002. Recordings of 20 s were made at the receiver position shown in Fig. 1, i.e., with microphones at 1 m above floor level, and with the center section between the two microphones at 0.5 m from the center section of the sump tank. The 20 s recordings were input into the Matlab software PsySound3 to compute sharpness,[11] roughness,[12] and pitch strength,[13] whilst loudness was obtained from the Brüel & Kjaer 2250 sound level meter.[14] Auditory tests were carried out using 7 s extracts of the audio recordings.

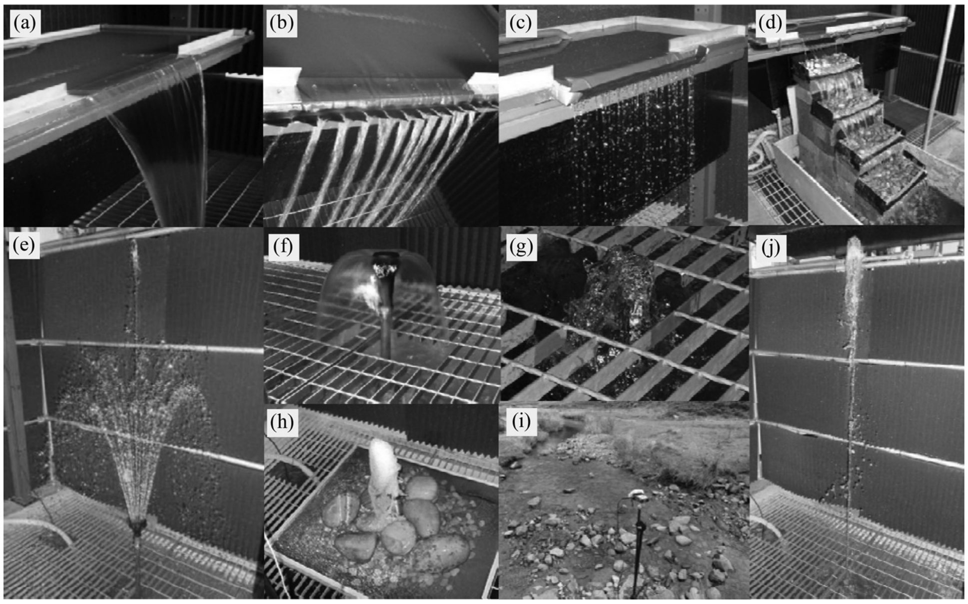

FIG. 2. Examples of water features tested, with sound codes given in parentheses (refer to Table I for features properties). (a) Plain edge waterfall (PEW). (b) Sawtooth edge waterfall (SEW). (c) Small holes' edge waterfall (SHW). (d) Cascade (CA). (e) Fountain (37 jets) (FTW). (f) Dome fountain (DF). (g) Large and shallow jet (LJT). (h) Foam fountain jet (FF). (i) Stream (field measurement) (ST). (j) Narrow jet (NJT).

III. THE EFFECTS OF DESIGN FACTORS ON ACOUSTICAL AND PSYCHOACOUSTICAL PARAMETERS

This section outlines the effects of flow rate, height of falling water, waterfalls' edge design, and impact materials on acoustical and psychoacoustical parameters. A considerable amount of data has been obtained from the research, but only key results are presented in graphical form to illustrate the findings.

A. Flow rate

Results obtained from the laboratory tests indicate that the equivalent continuous sound pressure level, L_{Aeq}, increases logarithmically with flow rate for all types of small to medium sized water features (waterfalls, fountains, jets, and cascades). This is illustrated in Fig. 3 for waterfalls and fountains, where large increases at low flow rates and small increases at high flow rates are observed. The only exception to this logarithmic trend is represented by the plain edge waterfall with a low height of falling water of 0.5 m [Fig. 3(a)]. Apart from this exception, all the features tested complied with the logarithmic trend of L_{Aeq} with flow rate, a trend which was also confirmed when the parameter used was loudness instead of L_{Aeq}.

This finding was compared with the results obtained by Fastl,[15] who measured the loudness of three large cascade structures operated at different flow rates. In contrast to the above-discussed results, Fastl's data show that loudness increases with flow rate without following a single predictable trend. This suggests that the acoustic properties of small and medium sized water features might not be applicable to larger water features. All the laboratory results also indicate that waterfalls have a smaller range of variation in L_{Aeq} and can easily produce higher sound pressure levels compared to fountains, jets, and cascades (65–75 vs 50–70 dBA), as they can use higher flow rates and larger amounts of water which produce more bubbles.

A frequency analysis indicates that the water sounds produced by all the features are mid- and high frequency dominant, with most of the energy contained in the 500 Hz–16 kHz octave bands. This is shown for a plain edge waterfall and a fountain in Fig. 4. The changes in flow rate appear

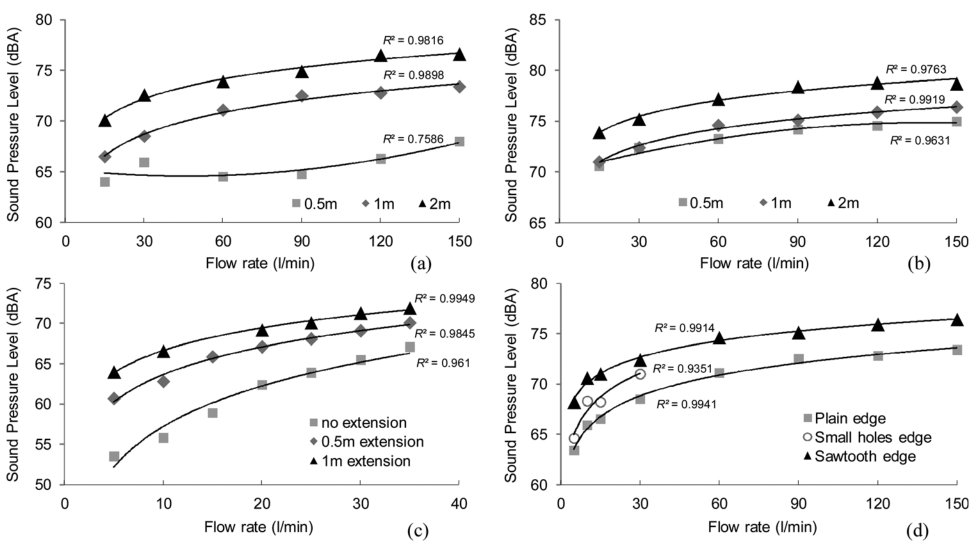

FIG. 3. Sound pressure level L_{Aeq} vs flow rate, with regressions and coefficient of determination R^2. (a) Plain edge waterfall of 1 m width with varying heights of falling water. (b) Sawtooth edge waterfall of 1 m width with varying heights of falling water. (c) Fountain (37 jets) placed at varying heights from water. (d) Waterfalls with different edge types (1 m width and 1 m height); the small holes' edge data are restricted in terms of flow rates, as only a limited amount of water can pass through its 2 mm holes.

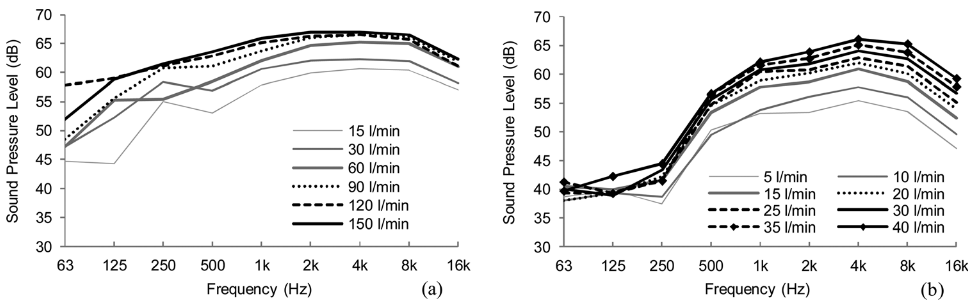

FIG. 4. Spectra obtained for different flow rates. (a) Plain edge waterfall of 1 m width and 1 m height of falling water. (b) Fountain (37 jets) with 0.5 m extension.

to affect the sound pressure level equally for all frequencies above 500 Hz (dominant range), whilst the low frequency changes tend to be variable and less significant for all water features except waterfalls [Fig. 4(a)]. Overall, results show that low frequency sounds cannot be easily produced by increasing the flow rate in features such as fountains, cascades, and jets, as the bubbles generated are too small. In contrast, waterfalls can generate low frequencies by increasing the flow rate (up to $\approx +10$ dB).

Regarding the effects of flow rate on psychoacoustical parameters, it can be noted that sharpness (typical values of 1.70–2.25 acum) and pitch strength (typical values of 0.05–0.10) exhibit no clear trends for waterfalls, whilst for cascades, fountains, and jets there is a small increase in sharpness with flow rate and the increase is linear (whilst pitch strength tends to be fairly constant). On the other hand, roughness decreases logarithmically with flow rate for all the water features tested (decreases of 0.10–0.30 asper). A sample of psychoacoustic results are discussed and illustrated in Sec. III D (Fig. 7).

B. Height of falling water

Looking back at Fig. 3, it is interesting to note that an increase in the height of falling water increases L_{Aeq} levels noticeably (+5–10 dB), with the exception of waterfalls operated at low flow rates for the 0.5 and 1 m impact heights. This suggests that waterfalls of low height, operating at low flow rates, produce similar sounds, a trend which is not observed in fountains [Fig. 3(c)]. It is also worth noting that the height from which water falls affects the shape of the frequency response, but the spectral changes observed vary for each feature and do not exhibit a predictable trend.

Sharpness and roughness tend to increase with the height of falling water, whilst the pitch strength decreases. However, the variations observed are not significant (sharpness $\approx +0.10$ acum, roughness $\approx +0.10$ asper, pitch strength ≈ -0.05), and no trends can be given due to the fact that only three heights were tested.

C. Waterfalls' edge design

Results shown in Fig. 3(d) indicate that higher L_{Aeq} levels are obtained when distributing the same amount of water over several streams (sawtooth edge and small holes' edge) rather than over one uniform stream (plain edge). Increases in L_{Aeq} are in the order of 2–3 dB. This is in line with results obtained from waterfalls with different widths that show increases in L_{Aeq} of 2–3 dB when the width is enlarged from 0.5 to 1.5 m. Tests made on constant width flow rates (i.e., identical flow rates delivered in terms of liters per meter) have also shown that a doubling in the width corresponds to an increase in L_{Aeq} of 3 dB on average.[16] This is in line with theory, as doubling the width corresponds to a doubling in the power of the sound source.

The spectra of Fig. 5 indicate that the plain edge design tends to be the most effective design for producing low frequencies, whilst the small holes' edge does not produce low frequencies and shows a spectrum's shape comparable to fountains [see Fig. 4(b)]. The proportion of high frequencies is reflected in the sharpness, as the small holes' edge produces a higher sharpness compared to the plain and sawtooth edges ($\approx +0.20$ acum). In contrast, the variations in roughness and pitch strength are small (roughness ≈ -0.05 asper for the small holes' edge, pitch strength $\approx +0.02$ for the sawtooth edge).

D. Impact materials

Impact materials can greatly affect the acoustical and psychoacoustical properties of water features. This is particularly true for low height waterfalls, such as the 0.5 m height sawtooth edge waterfall for which results are given in Fig. 6 for a flow rate of 30 l/min (typical operation). In Fig. 6, it can be seen that water is the impact material producing the highest L_{Aeq}, whilst plain solid surfaces, such as metal and concrete, produce lower levels (5–7 dB lower). This is due to the formation of vibrating bubbles in the water, whilst rigid surfaces, such as the metal plate and concrete blocks tested, do not allow the formation of bubbles and only exhibit limited impact sound. Stones like pebbles (30–60 mm) and gravel (10–20 mm) are other common impact materials. These present irregular surfaces that allow the formation of pockets of

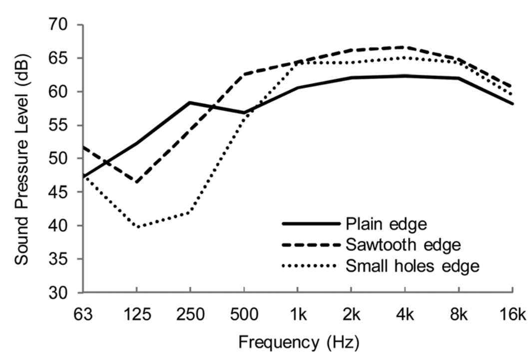

FIG. 5. Impact of waterfall's edge design on sound spectra (waterfall of 1 m width and 1 m height, with a flow rate of 30 l/min).

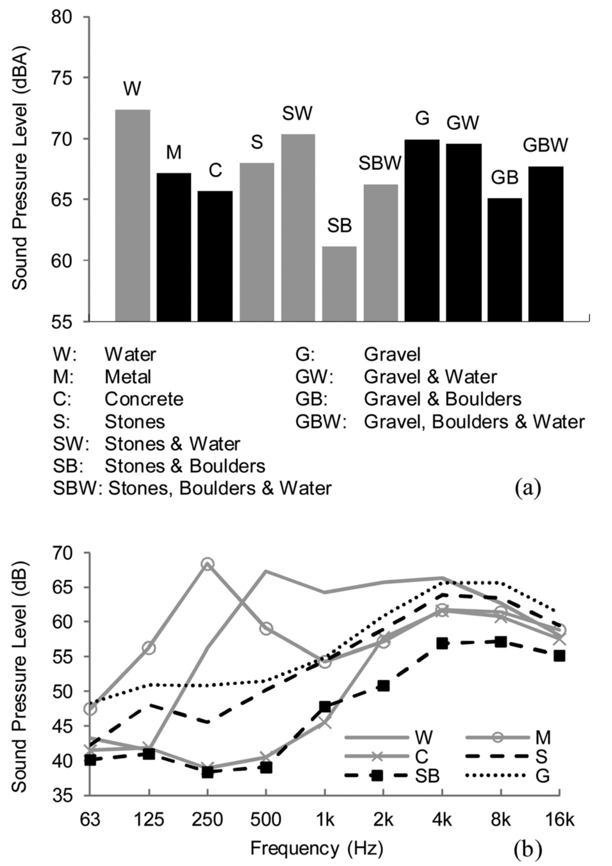

FIG. 6. The effect of impact materials on sound pressure level for a sawtooth edge waterfall of 1 m width and 0.5 m height of falling water, operating at a flow rate of 30 l/min. (a) L_{Aeq}. (b) Spectra.

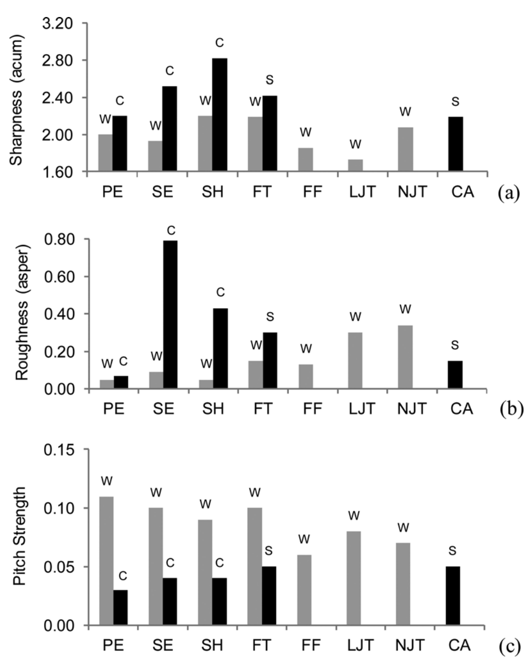

FIG. 7. The effect of impact materials (W: Water; C: Concrete; S: Stones) on the sharpness (a), roughness (b), and pitch strength (c) of a variety of water features. PE: Plain edge waterfall. SE: Sawtooth edge waterfall. SH: Small holes' edge waterfall. FT: Fountain (37 jets). FF: Foam fountain. LJT: Large jet (25 mm nozzle). NJT: Narrow jet (10 mm nozzle). CA: Cascade. The waterfalls were of 1 m width with a height of falling water of 0.5 m. The flow rate for all water features was 30 l/min, with the exception of LJT, NJT, and CA for which it was 15 l/min.

water and hence vibrating bubbles. The L_{Aeq} observed for stones and gravel is therefore higher than the one observed for plain surfaces (in the order of 2–4 dB higher).

Boulders (150–250 mm) can also be used over stones or gravel. These tend to make water slide over them, which limits bubbling sounds, hence resulting in L_{Aeq} levels that can be very low [e.g., large difference of 11 dB between the water (W) and the stones and boulders (SB) tests of Fig. 6(a)]. In line with previous findings, combinations of solid materials and water show that higher L_{Aeq} levels are obtained when water is present (water placed in small containers over impact materials).

In terms of spectra [Fig. 6(b)], water exhibits significantly higher levels than most impact materials at mid-frequencies (typically +5–10 dB in the range 250 Hz–2 kHz). Concrete, stones, boulders, and gravel are dominated by high frequencies, with concrete and boulders exhibiting very little low frequency content. Gravel is easily displaced by water, so that water pockets are easily formed and more low to mid-frequency sounds are produced than when stones are used. Figure 6(b) also shows that the metal plate has a high frequency spectrum similar to concrete, and a noticeable peak at 250 Hz that is due to a resonance in the plate. Differences between the materials are less pronounced when the flow rate is increased, as more pockets of water and bubbles are produced. Differences between water and solid materials are also reduced when the height of falling water is increased (e.g., maximum differences of 3 dB for waterfalls of 2 m height). For the fountains and jets tested without extensions (i.e., attached at water level), the differences observed between materials are much less significant than for waterfalls of low height (maximum differences in the order of 2–3 dB for L_{Aeq}). This can be explained by the fact that fountains and jets are mid–high frequency dominant, and therefore less dependent on the amount of large bubbles produced in water.

Psychoacoustic results are given in Fig. 7 for a variety of water features. In line with the results obtained for spectra, Fig. 7(a) shows that the sharpness increases with solid materials, the highest sharpness being produced by waterfalls over concrete and the lowest sharpness being produced by the large jet over water. Figure 7(b) also shows that roughness tends to increase with solid materials, whilst the pitch strength is higher when water is the impact material [Fig. 7(c)]. The variations are significant for sharpness (+1.09 acum) and roughness (+0.74 asper), but relatively small for pitch strength (+0.08). It can also be noted that these sharpness and roughness variations are much larger than when water is the only impact material considered (see also Secs. III A–III C).

E. Main findings

The flow rate can be increased to obtain higher sound pressure levels, but levels tend to become constant toward high flow rates. Waterfalls can generate low frequencies and these can be increased with flow rate (typically up to ≈+10 dB), unlike other features. Tests also showed that water tends to be the impact material producing more mid–low frequencies

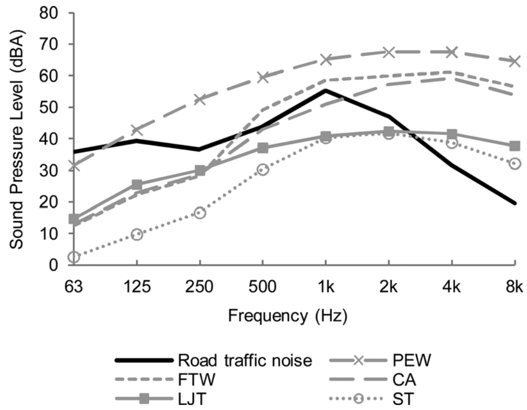

FIG. 8. A-weighted spectra of measured road traffic noise (200 m distance between motorway and receiver) and measured water sounds (see Table I for definitions of acronyms).

(+5–10 dB in the range 250 Hz–2 kHz) as well as higher sound pressure levels, whilst the use of hard materials increases the high frequency content and sharpness of the sound (up to $\approx$+1 acum), and decreases its overall sound pressure level (down to as much as ≈ -10 dB). Furthermore, changes in acoustical and psychoacoustical properties become less significant with increasing height and flow rate, in which case the impact of design factors other than height becomes negligible.

IV. ROAD TRAFFIC NOISE AND WATER SOUNDS

Dense road traffic with low temporal variability was considered representative of a real case scenario where masking by small to medium sized water features could be used (e.g., in a garden or park). The spectrum of road traffic noise was measured in a field at 200 m from the center of a busy motorway (M8 Edinburgh—Glasgow, UK) and is given in Fig. 8 (data averaging period of 1 min). This is the traffic noise that was used in the auditory tests of Sec. V, and has an A-weighted level of 56 dBA. Incidentally, it can be noted that the spectrum's shape of traffic noise did not vary significantly when closer to the motorway.

Together with road traffic noise, Fig. 8 shows a variety of water sound spectra that have been selected based on their large range in frequency content. In terms of human perception, expressed in Fig. 8 by the A-weighted sound pressure level, traffic noise is dominated by frequencies in the 250 Hz–2 kHz range, whilst most water sounds are characterized by the 500 Hz–8 kHz range. There is therefore a mismatch between the spectra of traffic noise and water sounds. This confirms the findings from Watts *et al.*[2] regarding the difficulty of generating low frequencies by using water sounds. However, results presented here show that a waterfall with a large flow rate (PEW) can generate high sound pressure levels at mid- and low frequencies (below 500 Hz). The fountain (FTW) and the cascade over stones (CA) are dominated by high frequencies, whilst the stream measured in the field (ST) has less high frequency content and is comparable to the waterfall (PEW) for its shape; the large jet (LJT) has the flattest frequency response. Although only the waterfall's result corresponds to a high flow rate, it can be noted that all the other water features would not produce much more low frequencies if their flow rate was increased (see Sec. III A). This clearly limits the spectral masking properties of most small to medium sized water features against road traffic noise.

V. PERCEPTUAL ASSESSMENT

Auditory tests were undertaken to provide insight into the subjective rating of water sounds used over road traffic noise. First, a test was carried out to identify the preferred sound pressure level of water sounds over road traffic noise, and second, another test was carried out to identify the preferred water sounds in the presence of road traffic noise. Twelve different water sounds were used in these tests (Table I), and were categorized either as waterfalls, fountains (made of one or more upward jets), or streams (note that LJT has been defined as a stream because of its very shallow and irregular distribution of water: Low pressure is present at its large nozzle's opening, therefore resulting in a unsteady operation of the pump and a high value of $L_{A10}-L_{A90}$). These

TABLE I. Properties of water sounds and road traffic noise used in the auditory tests, including acoustic and psychoacoustic parameters of the sounds normalized to 55 dBA. Category numbers: 1 = waterfall, 2 = fountain, 3 = stream. The numbers in italic were calculated from sounds including both road traffic noise and water sounds. Fountain extensions and jets were placed at water level; the large jet had a nozzle's diameter of 25 mm, and the narrow jet had a nozzle's diameter of 10 mm.

Sound code	Water feature type and category number	Impact material	Flow rate (l/min)	Height (m) and width (m)	$L_{A10}-L_{A90}$ (dB)		$L_{Ceq}-L_{Aeq}$ (dB)		Sharpness (acum)		Roughness (asper)		Pitch strength	
PEW	Plain edge waterfall—1	Water	120	1.0–1.0	1.1	*1.4*	−0.3	*2.8*	1.98	*1.70*	0.03	*0.04*	0.04	*0.07*
SEW	Sawtooth edge waterfall—1	Water	30	0.5–1.0	1.0	*1.6*	−0.1	*2.7*	1.92	*1.59*	0.05	*0.05*	0.10	*0.07*
SHW	Small holes waterfall—1	Water	30	0.5–1.0	0.7	*1.4*	−1.0	*2.5*	2.23	*1.71*	0.02	*0.04*	0.09	*0.08*
SHC	Small holes waterfall—1	Concrete	30	0.5–1.0	2.3	*1.7*	−1.5	*2.0*	2.95	*2.03*	0.23	*0.19*	0.03	*0.07*
FTW	Fountain (37 jets)—2	Water	30	—	1.4	*1.5*	−0.9	*2.7*	2.21	*1.67*	0.07	*0.08*	0.10	*0.08*
FTS	Fountain (37 jets)—2	Stones (pebbles)	30	—	1.5	*1.6*	−1.5	*2.5*	2.51	*1.82*	0.21	*0.13*	0.05	*0.08*
DF	Dome fountain—2	Water	30	—	1.6	*1.5*	0.3	*2.8*	1.96	*1.61*	0.07	*0.05*	0.14	*0.08*
FF	Foam fountain—2	Stones and boulders	30	—	2.3	*1.6*	−0.2	*2.8*	1.91	*1.61*	0.09	*0.09*	0.05	*0.07*
LJT	Large jet—3	Water	15	—	4.9	*2.1*	4.9	*2.9*	1.73	*1.42*	0.28	*0.19*	0.08	*0.07*
NJT	Narrow jet—2	Water	15	—	1.9	*1.6*	−0.9	*2.5*	2.09	*1.67*	0.19	*0.16*	0.07	*0.08*
CA	Cascade (4 steps)—3	Stones (pebbles)	15	—	1.2	*1.4*	−1.3	*2.7*	2.21	*1.71*	0.10	*0.09*	0.05	*0.08*
ST	Stream—3	Stones and water	N/A	—	2.4	*1.7*	−1.4	*2.5*	1.99	*1.61*	0.29	*0.21*	0.06	*0.08*
RTN	Road traffic noise	—	—	—	2.7		7.8		1.04		0.03		0.09	

sounds were played over road traffic noise recorded in a field located 200 m from the center of a busy motorway (see Sec. IV). The sound spectra representative of a variety of water sounds were given in Fig. 8 together with the traffic noise measured (the normalized spectra of all the water sounds used in the auditory tests can be found in Ref. 17).

A. Preferred sound pressure levels

1. Methods

The procedure used was the same as the one developed by Jeon *et al.*,[4] with a constant traffic noise level played at 55 dBA, and with water sounds played at either 49, 52, 55, 58, or 61 dBA (i.e., −6, −3, 0, +3, or +6 dB relative to the road traffic noise level). The test was carried out for six different water sounds: SHW, PEW, CA, FTW, FF, and LJT (refer to Table I for details). The listening test included ten paired comparisons per water sound, for a total of sixty paired comparisons. Furthermore, ten comparisons were repeated in order to identify the consistency of subjects. In view of statistical validity, the sequence of paired comparisons was randomized, so that sounds were presented in a different order for each subject.

Thirty-four subjects who reported normal hearing ability participated in the test (seventeen males and seventeen females), all of whom were either students or researchers working at Heriot-Watt University (age and cultural groups' details given in Sec. V A 2). The test was carried out in the anechoic chamber of Heriot-Watt University, a highly insulated space with a background noise level of around 21 dBA during tests (including noise from the computer used). Instructions were initially given to the subjects, who had to imagine that they were relaxing in a balcony or garden where they could hear road traffic noise from a nearby motorway as well as a water feature (same as Ref. 2). Binaural signals were played back from a computer through closed headphones (Beyerdynamic DT 150), where each paired comparison consisted of 7 s of sound 1, 1 s of silence, 7 s of sound 2, and 3 s of silence before the next pair was played. For each comparison, subjects had to select the sound that they found more peaceful and relaxing (i.e., more tranquil as defined in Ref. 2). Considering the similarities between some of the comparisons, subjects had the option to select "no preference," but were not encouraged to do so. No visual images were used. Five paired comparisons were initially played for familiarization with the methods. Once the subject was clear about the procedure, the actual test could begin. This consisted of ten paired comparisons played in an automated sequence, after which the subject was free to take a break before continuing with the following ten pairs, in order to maintain a high concentration level. The test typically lasted 30 min per subject, including instructions and breaks.

2. Results and analysis

Twenty-nine subjects (fifteen males and fourteen females of age distribution 19–34 years, average age 26.3 years, standard deviation 4.3 years) passed the consistency test (consistent judgments within a 95% confidence interval) and were retained for the analysis of results. The cultural groups' composition was as follows: "White" (10), "Middle Eastern" (6), "Asian" (11), and "African/Caribbean" (2), where the numbers in parentheses correspond to the number of subjects present within each group.

Results are shown in Fig. 9 with normalized preferences given on the vertical axis [preferences defined over the range −2 (never preferred) to +2 (always preferred)]. The no preference option was chosen only 5% of the time, in which cases no preferences were counted for the levels concerned. For the four sounds SHW, CA, FTW, and FF, the preferred water sound pressure level was the same as the road traffic noise level (0 dB difference, i.e., 55 dBA level), whilst for the remaining two sounds PEW and LJT, the preferred level was 3 dB below road traffic noise (i.e., 52 dBA level). It is interesting to note that PEW and LJT are the sounds with the highest low frequency content, i.e., with the better masking spectra, and a preferred sound pressure level lower than all the other water sounds. No statistically significant difference in responses was found between the different gender, age, and cultural groups (Mann-Whitney test, $p > 0.05$ in each case).[18]

3. Discussion

Overall, these results confirm the findings of Jeon *et al.*,[4] according to which the water sounds should be similar or not less than 3 dB below the urban noise level. The results obtained here also show that preferences are independent from the subjects' sample (i.e., gender, age, and culture). Furthermore, it is worth noting that You *et al.*[19] also obtained the same results regardless of whether road traffic noise was played at 55 or 75 dBA.

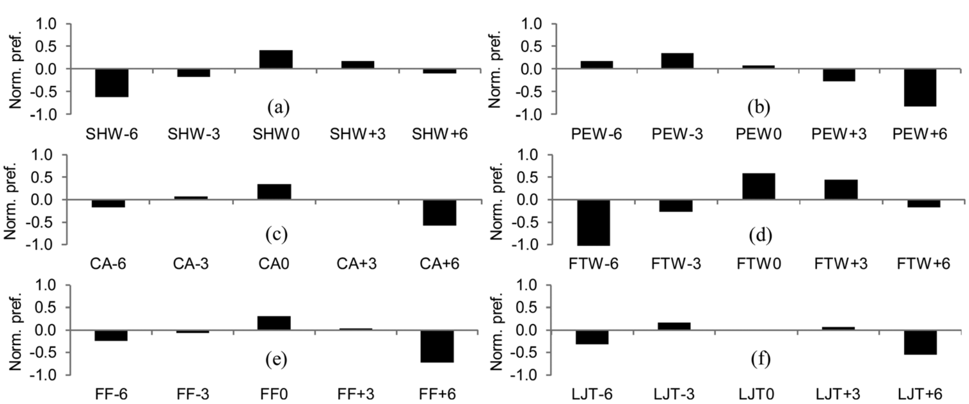

FIG. 9. Preferred water sound pressure levels: normalized preference values as a function of relative sound pressure level. (a) Small holes' edge waterfall (SHW). (b) Plain edge waterfall (PEW). (c) Cascade (CA). (d) Fountain (FTW). (e) Foam fountain (FF). (f) Large jet (LJT).

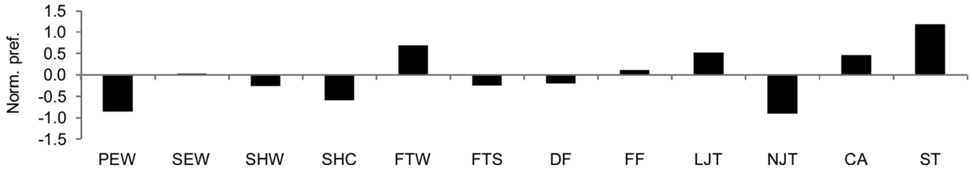

FIG. 10. Preferred water sounds: normalized preference values as a function of water sounds (see Table I for definitions of acronyms).

B. Preferred water sounds

1. Methods

In this test, paired comparisons were made between 12 water sounds (Table I) played over road traffic noise. All the water sound pressure levels and traffic noise levels were played at 55 dBA, as results of Sec. V A 2 have shown that a difference of 0 dB between water sounds and traffic noise tends to be preferred. A total of 76 paired comparisons were carried out per subject, including the 10 repetitions made for the analysis of consistency. Furthermore, five additional paired comparisons were made to examine the preferred edge type of a waterfall and the preferred impact material of a sawtooth edge waterfall. This required using three additional water sounds not shown in Table I: (1) A plain edge waterfall over water, with a flow rate of 30 l/min; (2) a sawtooth edge waterfall over stones, with a flow rate of 30 l/min; (3) a sawtooth edge waterfall over stones and boulders, with a flow rate of 30 l/min. The sequence of paired comparisons was randomized for all tests.

Similar to the test made for preferred sound pressure levels, thirty-four subjects who reported normal hearing ability participated in the test (seventeen males and seventeen females), all of whom were either students or researchers (different sample than the previous one). The methods for instructing subjects and presenting the paired comparisons were identical to those described in Sec. V A 1, but the no preference option was not given as differences between the sounds were not subtle. The test typically lasted 35 min per subject, including instructions and breaks.

2. Results and analysis

Thirty-one subjects (fifteen males and sixteen females of age distribution 20–45 years, average age 27.8 years, standard deviation of 4.9 years) passed the consistency test (consistent judgments within a 95% confidence interval) and were retained for the analysis of results. The cultural groups' composition was as follows: "White" (14), "Middle Eastern" (7), "Asian" (6), and "African/Caribbean" (4), where the numbers in parentheses correspond to the number of subjects present within each group.

The results given in Fig. 10 [preferences defined over the range -2 (never preferred) to $+2$ (always preferred)] and Table II indicate that the preferred water sounds are the natural stream ST, the fountain made of 37 jets FTW, the large jet with a low flow rate and shallow distribution of water LJT, and the cascade with four steps CA. In contrast, the least liked sounds are the waterfalls with small holes SHW and SHC, the waterfall with a plain edge and a very large flow rate PEW, and the single jet with a narrow nozzle NJT. A statistically significant correlation was found between the category numbers of Table I and the preferences obtained, suggesting that stream sounds are preferred to fountain sounds, which are in turn preferred to waterfall sounds (Spearman test, $\rho = 0.678$, $p < 0.05$). Results of Fig. 10 also indicate that water is the preferred impact material (FTW preferred to FTS, and SHW to SHC). As in the case of the preferred sound pressure level test, a statistical analysis of the results indicated no significant difference between the different gender, age, or cultural groups (Mann-Whitney test with $p > 0.05$ in each case).[18]

The ratings of each sound followed a normal distribution between subjects with the Kolmogorov–Smirnov test showing no significant deviation from normality with $p > 0.05$, apart from the ratings obtained for LJT with $p = 0.043$. This normality of preference judgments, with a clear peak and decline on either side, suggests a stable profile for preference judgments which can generalize to the wider population. However, a concordance analysis indicated a degree of agreement between subjects that was not high (Kendall's coefficient of concordance $W = 0.32$, statistically significant at $p = 0.001$).[18,20] This low concordance value was further explored by latent class analysis,[21] a form of regression analysis that can handle non-parametric data and identify clusters or sub-groups (latent classes) in a data set. Latent class analysis showed that the subjects' sample was divided into two clusters in terms of preference judgments for four of the twelve sounds. These were sounds PEW, SHW, and LJT at $p < 0.01$ and sound DF at $p < 0.05$. When these four sounds were excluded, the concordance coefficient W increased to 0.43. The results obtained for the different clusters are given in Table II (Cluster 1: 17 subjects; cluster 2: 14 subjects), where it can be seen that the ranking variations are actually not significant, as the ranking

TABLE II. Ranking of preferred water sounds obtained from all subjects retained for the analysis, together with clusters' ranking obtained from latent class analysis. The preferences are listed as normalized preference values.

	All subjects		Cluster 1		Cluster 2	
Sound ranking	Sound code	Norm. pref.	Sound code	Norm. pref.	Sound code	Norm. pref.
1	ST	1.19	ST	1.12	ST	1.27
2	FTW	0.70	LJT	0.84	FTW	0.99
3	LJT	0.52	FTW	0.46	CA	0.73
4	CA	0.46	CA	0.25	LJT	0.13
5	FF	0.11	FF	0.20	SEW	0.13
6	SEW	0.03	DF	−0.03	FF	0.00
7	DF	−0.19	SEW	−0.05	SHW	−0.08
8	FTS	−0.24	FTS	−0.12	DF	−0.39
9	SHW	−0.25	SHW	−0.40	FTS	−0.39
10	SHC	−0.58	SHC	−0.50	PEW	−0.60
11	PEW	−0.85	NJT	−0.72	SHC	−0.68
12	NJT	−0.90	PEW	−1.06	NJT	−1.12

TABLE III. Ranking groups with corresponding averages of acoustic and psychoacoustic parameters, and corresponding correlation coefficients (Spearman test). The numbers in italic were calculated from sounds including both road traffic noise and water sounds.

Sound ranking groups	$L_{A10}-L_{A90}$ (dB)		$L_{Ceq}-L_{Aeq}$ (dB)		Sharpness (acum)		Roughness (asper)		Pitch strength	
1–4	2.5	*1.7*	1.0	*2.7*	2.04	*1.60*	0.19	*0.14*	0.07	*0.08*
5–8	1.6	*1.6*	−0.4	*2.7*	2.08	*1.66*	0.11	*0.08*	0.09	*0.08*
9–12	1.5	*1.5*	−0.9	*2.5*	2.31	*1.78*	0.12	*0.11*	0.06	*0.08*
Correlation coefficient	−1.00[a]	*−1.00*[a]	−1.00[a]	*−0.87*	1.00[a]	*1.00*[a]	−0.50	*−0.50*	−0.50	—
1–3	2.9	*1.8*	1.8	*2.7*	1.98	*1.57*	0.21	*0.16*	0.08	*0.08*
4–6	1.5	*1.5*	−0.5	*2.7*	2.01	*1.64*	0.08	*0.08*	0.07	*0.07*
7–9	1.3	*1.5*	−0.7	*2.6*	2.23	*1.71*	0.10	*0.07*	0.09	*0.08*
10–12	1.8	*1.6*	−0.9	*2.4*	2.34	*1.80*	0.15	*0.13*	0.05	*0.07*
Correlation coefficient	−0.40	*−0.32*	−1.00[a]	*−0.95*	1.00[a]	*1.00*[a]	−0.20	*−0.40*	−0.40	*−0.45*
1–2	1.9	*1.6*	0.2	*2.6*	2.10	*1.64*	0.18	*0.15*	0.08	*0.08*
3–4	3.1	*1.8*	1.8	*2.8*	1.97	*1.57*	0.19	*0.14*	0.07	*0.08*
5–6	1.7	*1.6*	−0.2	*2.8*	1.92	*1.60*	0.07	*0.07*	0.08	*0.07*
7–8	1.6	*1.6*	−0.6	*2.7*	2.24	*1.72*	0.14	*0.09*	0.10	*0.08*
9–10	1.5	*1.6*	−1.3	*2.3*	2.59	*1.87*	0.13	*0.12*	0.06	*0.08*
11–12	1.5	*1.5*	−0.6	*2.7*	2.04	*1.69*	0.11	*0.10*	0.06	*0.08*
Correlation coefficient	−0.93[a]	*−0.68*	−0.84[b]	*−0.23*	0.31	*0.66*	−0.60	*−0.45*	−0.53	*0.13*

[a]Correlation is significant at the 0.01 level.
[b]Correlation is significant at the 0.05 level.

positions of water sounds do not vary markedly (up or down two positions at most). This justifies the analysis based on different ranking groups shown in Table III, where groups of either two, three, or four sounds are given. For example, group 1–4 includes the four sounds rated on top by the 31 subjects, i.e. ST, FTW, LJT, and CA. Similar to Table I, the data of Table III were calculated for water sounds either including or not including road traffic noise. As the preference tests were carried out in the presence of traffic noise, the analysis should be primarily based on the italic numbers of Table III; results obtained from the water sounds alone are also given in the table, as subjects have the potential to focus on the most positive and distracting sound.[2,8]

Correlations have been examined between ranking positions and the averages of acoustical and psychoacoustical parameters of each group, and the values obtained for Spearman's correlation coefficient are given in Table III. Spearman's tests indicated that the complexity of each individual water sounds does not lead to good correlations between ranking positions and any acoustical or psychoacoustical parameter. This is true when individual sounds are used for correlation tests, as well as when groups made of two sounds are used (bottom of Table III). However, some trends can be observed when the analysis is made for groups including more than just two sounds. For example, analysis made for the three groups 1–4, 5–8, and 9–12 indicates that the preferred water sounds have larger temporal variations in level ($L_{A10}-L_{A90}$), larger low frequency content ($L_{Ceq}-L_{Aeq}$), and lower sharpness; on the other hand, there are no correlations with roughness and pitch strength.

The results obtained for the preferred waterfall's edge are given in Fig. 11(a), where it can be seen that the sawtooth edge type is preferred to the small holes' edge, which is in turn preferred to the plain edge, which has a significantly lower rating. No correlations were found between these preferences and any acoustical or psychoacoustical parameter, but these results confirm that the sound produced by a plain edge waterfall tends not to be liked. Figure 11(b) illustrates preferences between different impact materials, showing that the use of boulders over stones is preferred to water, which is in turn preferred to stones alone. Previous results suggested that water is preferred to solid materials, but Fig. 11(b) indicates that this is not necessarily true. This ranking was correlated with higher values of $L_{A10}-L_{A90}$ ($\rho = -0.87$).

3. Discussion

Jeon *et al.*[5] found that water sounds defined by the word freshness had a higher sharpness, whilst water sounds defined by the word calmness had a lower sharpness. This is in line with the results obtained here, as the perceptual assessments were based on peacefulness and relaxation (i.e., calmness).

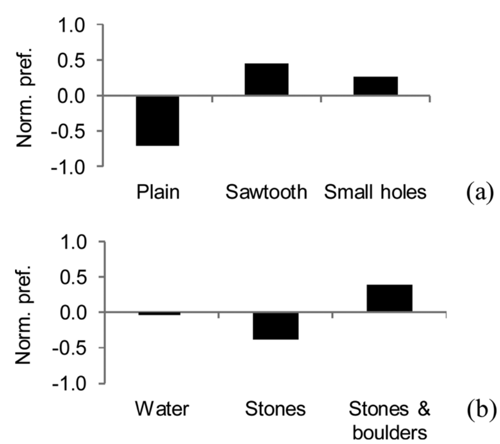

FIG. 11. Preferred waterfall's edge (a) and preferred impact material for a sawtooth edge waterfall (b), shown as normalized preference values. The waterfalls were of 1 m width with a height of falling water of 0.5 m and a flow rate of 30 l/min.

However, the preference of low sharpness contrasts with the findings of Watts *et al.*,[2] which showed that water sounds with higher sharpness were more highly rated in terms of tranquility. In that respect, it should be noted that the present study tested a variety of upward and downwards flows, whilst Watts *et al.*[2] examined only one downwards stream with varying impact materials. The latter case is comparable to the waterfalls tested, for which it was found that boulders were preferred to water as the impact material (i.e., higher sharpness). This might be due to the fact that a downward stream with lower sharpness tends to be associated with man-made sounds such as water falling into a drain or container, and these tend not to be liked.[2] Sharpness might then not be the key factor for driving preference of all types of water features, whilst temporal variations might be, according to the results obtained. This will have to be examined in more detail by future research, together with the meaning and evocative effect of the water sounds. The latter could justify the poor ratings obtained for PEW and NJT, if tests were to confirm that PEW is evocative of water falling into a drain or container, and that NJT resembles a water tap (i.e., man-made sounds).

It is also worth pointing out that the shallow stream sound (ST) was the only field recording used in these tests, but was by far the preferred water sound. This stream showed large temporal variations and a strong spatial quality clearly reflected in the left and right channels of the binaural recording (the sound was measured at the junction of two streams), all characteristics which were less pronounced in the laboratory generated sounds. This suggests that the use of multiple features as sound sources can increase envelopment and improve sound perception, an aspect that will need to be examined in more detail by future soundscape research.

VI. CONCLUSIONS

This study examined the design of water features to be used in gardens or parks where road traffic noise is audible, in view of improving the soundscape of such spaces. The acoustical and psychoacoustical analysis has shown that a great variety of water sounds can be produced by varying the design of small and medium sized water features (flow rate, height of falling water, waterfall's edge, and impact materials), and that estimations can be made on how these factors affect sound pressure levels, frequency content, and psychoacoustic parameters. Most of the small to medium sized water features tested could not generate low frequencies comparable to road traffic noise, but unlike the streams tested by Watts *et al.*,[2] results have shown that waterfalls with large flow rates can generate low frequency levels that are similar to those of road traffic noise.

Auditory tests indicated that the sounds of natural streams and fountains made of upward jets tend to be more suitable for improving peacefulness and relaxation in the presence of road traffic noise, whilst waterfall sounds are not appropriate. This suggests that masking purely based on spectral analysis cannot be the driving criterion for designing water features, as waterfalls presented better spectral properties for masking but tended not to be preferred. Perceptual results also suggested that flat surfaces made of hard impact materials (i.e., sounds with high sharpness) are poorly rated and should not be used. Furthermore, analysis made on groups of sounds showed that low sharpness and large temporal variations were preferred on average, but the complexity of physical and perceptual properties pointed out that no individual parameter can be considered as a key factor for driving preference, so that further work will be needed to characterize preferences.

Auditory experiments also indicated that the water sounds should be similar or not less than 3 dB below the road traffic noise level, further validating results obtained by Jeon *et al.*[4] and You *et al.*[19] It is important to remember that these findings are specific to gardens and parks in the context of peacefulness and relaxation. For example, soundscape preferences and contexts can be different in urban squares, as suggested by the significant correlations with "freshness" (i.e. high sharpness) found by Jeon *et al.*[5]

Although the analysis focused on road traffic noise and outdoor environments, it can be noted that the water sounds examined were representative of features that can be installed in both outdoor and indoor spaces such as gardens, parks, hotel lobbies, offices, and restaurants, so that the design findings of Sec. III are applicable to both indoor and outdoor conditions. In order to develop the research presented, perceptual assessment of aural and visual interactions will be examined by future work. Furthermore, research will be needed to examine the effects of the meaning of water sounds on preferences, as well as to examine the use of multiple water features in view of increasing sound envelopment and improving the soundscape.

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